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WIND-EROSION CONTROL

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Introduction

Wind erosion has been active in some degree since prehistoric times but has become much more active and more destructive with the increased activity of man. This "accelerated" erosion has been caused by wrong methods of treating the land or by the use of the land for purposes to which it was not suited.

Wind erosion is perhaps most active in arid and semiarid regions where the land surface is often dry and vulnerable to erosion and the protective vegetation is sparse or absent. The wind may also move large quantities of soil material in humid regions; and, agriculturally considered, wind activity in such regions may be more important because of the greater value of much of the land affected.

Today wind erosion is the most active, the most potent, depleter of soil fertility on most of the Great Plains as well as in other areas. It is one of the greatest natural hazards in the spring and winter wheat areas. Great Plains soils are noted for their high fertility; but this fertility, as in all soils, is largely bound up in the upper, humus-bearing zone. It has taken nature centuries to create this rich topsoil. To lose it during a storm or a series of storms is to lose for immediate crop production the fruit of nature's efforts for centuries.

Soil blowing has become a greater problem in Plains agriculture as new areas have been brought into cultivation. This is not necessarily because the hard sweeping winds have become more intense, but because the natural vegetation has been removed and its beneficial effects on the soil have been destroyed.

The greatest danger from soil blowing is in early spring, when the highest monthly velocities of the year are encountered and the land is most susceptible to blowing. Soil blowing may be serious any time of the year if not stopped by the use of appropriate control measures or prevented by a suitable cover of vegetation.

Any comparatively level field devoid of a covering of vegetal matter may blow if the soil is finely pulverized or tightly and smoothly crusted (figure 1.) The more sand the soil contains the greater is the likelihood of blowing. Once a field has started to blow, the condition will normally grow worse unless control methods are used. During hard sweeping windstorms, "eternal vigilance" and prompt action are necessary to detect blow spots and prevent them from spreading over vast areas.

The lands of the High Plains region originally were occupied by vegetation that over the centuries had proved best equipped to thrive under each particular soil and climatic condition. Under natural conditions soil was less exposed to wind action even during prolonged droughts because the residues of the last season's growth remained as a protective covering until rains, however long delayed, came to stimulate new growth. Wind erosion also is a serious problem on many of our muck lands and in many areas along the Atlantic and Pacific Coasts as well as along the Great Lakes and other places.

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Figure 1.--Cotton on sandy, tightly crusted field badly damaged by wind erosion. In some spots the topsoil is blown out to the subsoil. Soil excellent for range grasses but unsuited for cultivated crops.

The destruction of the natural cover incident to placing the land in cultivated crops or to overgrazing makes it necessary to maintain an effective substitute for the original cover. If this is not done, exposure of the soil to the wind for even short periods may allow severe erosion to take place. The maintenance of an adequate vegetal cover, therefore, becomes the primary goal of all wind-erosion control efforts (fig. 2.). The soil-blowing hazard has always been greatest in seasons of drought, after crop failures, and in places or on soil types poorly adapted to accumulate moisture (4).[2] Thus, in contrast to water erosion where the greatest erosion hazard exists in those areas where erosion-producing rains are most frequent, the wind-erosion hazard develops in those areas where erosion-producing rains are less frequent.

Soil Blowing

The rate of soil flow under a wind force varies inversely with the roughness of the surface (10, 11). Surface roughness in turn is dependent on the heights and lateral frequency of the surface obstructions.

The initial rate of soil flow over cultivated soils is much less when such soils are ridged than when the soil surface is smooth (11). This is because ridges reduce the wind velocity for some distance above the average surface of the land and trap soil on the leeward side. Ridges, however, produce greater velocities of wind flow over the crest of the ridge; also greater eddying. This results in a more rapid rate of erosion at the crest of the ridge. The initial net effect of ridging on these two sets of opposing forces is a reduction in the rate of erosion (fig. 3). As the field surface becomes leveled again by the trapping of soil in the furrows and the wearing down of the ridge crests, the effect of these two sets of forces tends to become reversed. The ridges lose their effectiveness and erosion is resumed as if the ridges were never formed.

[2] Figures in parenthesis refer to Literature Cited.

Figure 2.--Weeping lovegrass protects soil from wind erosion. Dust blowing in background is from unprotected land.

Figure 3.--Newly constructed ridges trap eroding soil on leeward side. As the field becomes leveled by the filling of the furrows and the wearing down of the crest of the ridges erosion continues as though the field had never been ridged.

Listing the soil at right angles to prevailing winds, either solid or every other row, or in strips in conjunction with planting to corn or other row crops, was tried at Colby, Kans., in 1914 during a devastating duststorm (4). This listing was followed by a rainy period after the first week in May, during which it rained 9 out of 11 days. These showers brought up the seeds that had been planted, sprouted the weed seeds which were abundant everywhere, and kept the soil from blowing long enough to give crops and weeds a chance to become established.

That fall an abundance of moisture enabled fall wheat to make a good growth before winter set in. The following spring there were only a few bare fields, mostly where the wheat was sown too late to make enough growth to cover the ground. Most fields were covered with growing wheat, heavy stubble, corn or sorghum stalks, or weeds. Although high winds were frequent during the spring months, the only serious blowing was on the late-planted wheatfields where the vegetation was not enough for protection.

The absence of vegetal cover was responsible for the serious soil blowing that occurred in the Colby, Kans., area in 1935 (4). The lack of rain during the fall of 1934 made it impossible to secure stands of winter wheat over most of the territory. In areas where moisture was enough to start the crop, lack of precipitation during the winter months resulted in not enough moisture to sustain the plants. Practically all fields that had been prepared for wheat were without a protective cover of vegetation when the strong winds started to blow in the spring of 1935. Furthermore, because the drought of 1934 caused a shortage of fodder for livestock, wheat stubble, corn and sorghum stalks, and Russian thistles and other weeds were grazed off closely or harvested for feed. Even native buffalograss pastures were so heavily overgrazed that the remaining vegetation was not enough to protect the soil.

The rate of soil flow is at a minimum at the windward edge of an eroding field and in most cases increases steadily to the leeward side. This increase in the rate of soil flow, which varies widely with different soil types, apparently is due to three main factors (7); namely, the steady increase in amounts of erosive particles, the cumulative degree of abrasion resulting from the impacts of saltation, and the gradual decrease in surface roughness in the direction of the wind. The steady increasing accumulation of the erosive fractions on the surface of the ground produces a condition that is necessarily more susceptible to erosion by wind until, for material composed only of erosive fractions, the susceptibility as measured by the rate of soil flow is the highest possible for the particular soil type and wind velocity.

The threshold velocity--minimum velocity of wind required to start and continue the movement of soil--is least for particles ranging from 0.05 to 0.15 mm. in diameter (5). These require a wind velocity of 8 to 9 miles per hour at 6 inches above the ground. Higher threshold wind velocities are required to move soil particles both above and below these sizes.

The movement of erodible material in uniform mixtures containing coarse nonerodible fractions under any velocity of wind ceases as soon as the surface becomes protected by coarser aggregates. In such mixtures, the amount of soil removed under a definite wind velocity varies logarithmically with the ratio of erodible to nonerodible fractions present. A satisfactory degree of protection of a bare soil against wind erosion is given by that size of aggregate which is just large enough to withstand movement by the wind.

The rate of soil flow over dry dune formations varies as the cube of the difference between the existent velocity and the threshold velocity (10). The rate of soil movement does not remain constant. In small areas or narrow strips, it diminishes with time and ceases after the surface becomes stabilized with soil fractions too coarse to be moved by the wind. Stabilization of the residual soil of fields that are not stripcropped--if wind direction is constant--may require many days or weeks because of the continual disintegration of clods and surface crust by abrasion from the bouncing soil particles. Shifting of wind direction, which is common in the Great Plains, favors a continual erosion of large blocks of land. Stripcropping, together with proper methods of soil trapping, reduces and usually eliminates the movement of soil by wind.

Soil loss by wind erosion was found to vary directly as the 2.5 power of the surface drag of the wind and the 3.5 power of the percent of soil fractions less than 0.42 mm. in diameter (12). It varied inversely as the 0.8 power of the weight of surface residue. Other elements of soil structure and surface residues influence the phenomenon of soil erosion by wind. Soil conditions at the immediate surface, such as crusting, stability of structure, puddling, and grading of the materials on the immediate surface by the impact of raindrops, as well as the effects of freezing, thawing, wetting, and drying all play a part.

Relation of Kind of Soil to Wind Erosion

Although almost any soil will blow if the physical conditions are right, the sandy soils are perhaps the most susceptible. The soil conditions most favorable for blowing are a smooth, finely pulverized surface free from a growing crop, weeds, or crop residue. A soil is least subject to blowing when it is covered with growing vegetation, weeds, or crop residue (fig. 4) or, if without vegetal cover, when it is rough and cloddy.

Figure 4.--Sudangrass stubble left anchored at the top of the ground provides excellent protection against wind erosion.

Bare, dry soils are subject to blowing when the wind velocity is high. Damage from this source has increased during the last few years because of extended drought periods and the increase in the cultivated acreage. In the Great Plains, sands and very sandy soils offer so little resistance to blowing that they cannot be safely cultivated and should be kept in or put back to grass. Heavy soils that form tenacious lumps and clods are least subject to blowing, and on them ordinary tillage practices can usually be employed with safety. Between these extremes is a large acreage of soils that are highly productive but on which special precautions and treatments are necessary to prevent or control soil blowing.

Experience over the last 20 to 30 years in the 14-20-inch rainfall belt has revealed the dangers of farming these soils. It has shown that on gentle and steeper slopes none of the shallow, moderately sandy and deep loose sandhill soils can be kept productive under cultivation (13) (fig. 5). Shallow hardlands, both flat and sloping, have undergone severe erosion in all areas of less than 18 inches average rainfall. Nearly level medium-textured moderately sandy lands, on the other hand, have resisted erosion under rainfall as low as 16 inches when suitable wind-erosion control practices were used.

Medium-depth hard lands have a fair to good record of performance, but where the rainfall is less than 17 inches a program of alternate cultivation and restoration under sod is required to avoid the severe damage.

Experience indicates that the hard lands deteriorate more slowly than the sandy lands. On such lands the difficulty of maintaining crop residues and of getting up crop stands are reliable signs of overuse.

The length of safe periods of cultivation necessarily varies with soils and climatic conditions. Deep, loamy sands in areas of 18 to 20 inches of rainfall offer fair possibilities

Figure 5.--Sandy soil, unfit for growing cultivated crops, should be returned to grass. Here sand lovegrass is being seeded in a stubble of sorghum and rye which will hold the land from blowing until the grass gets started.

of maintaining fertility and stability against wind erosion when green manure crops are used in the rotation. The deep, nearly level hard lands, the best of the High Plains wheat soils, can be safely farmed with appropriate precautions.

These findings parallel very closely the observations made in the Prairie Provinces of Canada, where it was found that regardless of conditions in different localities there are some definite principles that have general application (16). Among these are that summer fallow may be used on medium loam soils under proper conditions, but sandy or clay soils require the protection of vegetal cover. This means that plowed fallow, though suitable on loams, is not safe at all on sand or clay unless protective cover crops are planted. These more difficult soil types, therefore, should be protected either with a crop or trash cover or both.

It is generally true that wind with a wide unbroken sweep carries more drifting material than it does over narrow strips and therefore its sandblast action is greater on unstripped land. This seems to be at least one reason why stripcrop farming assists in control in most if not all localities (fig. 6).

In solving the soil-drift problem, one of the first requirements is to determine the soil types and past cropping history and to remove from cultivation as soon as possible such areas as are not suited for cultivation.

It is important to note that, although any fallowed piece of land may drift, some fallows have remained remarkably stable. Soils do not all erode with equal ease. For example, medium-textured soils do not erode as readily as others. Medium-textured loams that are not extremely high in organic matter do not drift readily unless improperly managed, but sandy soils and some clays are difficult to manage.

Soil which has never been deprived of its native vegetal covering by cultivation, or is being cultivated for the first time, is fairly resistant to wind erosion.

Light sandy soils are extremely subject to drifting. It is practically impossible to summer fallow this type of land, even in strips as narrow as 4 rods, without serious danger of drifting. Furthermore, records show that because of the low water-holding capacity of such soils and the frequent damage from soil drifting, yields on fallow generally are no higher and may even be lower than yields on stubble land. Consequently, fallowing

Figure 6.--The cotton plants on the left have trapped soil blown in from unprotected field at far left. Once the soil is trapped it remains in place as the wind cannot set it in motion again.

this type of soil for moisture conservation is of questionable value. If done, it should be confined to those seasons when the moisture in the soil is not enough to justify seeding a crop. These soils should be seeded to grass and kept in pasture permanently where feasible. Where planted to grain continuously, a rotation of wheat and fall rye is commonly used in the spring wheat area with the rye drilled directly into the wheat stubble. The rye stubble should be left until the following spring. The wheat may then either be seeded with a one-way disk with seeder attachment, or the land may be plowed, packed, and seeded immediately. Both crops are cut as high as possible so that the stubble may be left to collect snow and protect the soil against wind erosion (fig. 7).

Soil drifting may occur on sandy soils despite these measures. It is essential, therefore, to observe conditions in the fields at all times and, when necessary, plow furrows through danger spots at the first signs of drifting. Knolls that are highly subject to drifting should be seeded permanently to grass.

Clay soils are subject to drifting. They are usually fairly uniform in texture, and drifting may start in any part of a field or over an entire field at one time. Once started, drifting is severe even in narrow strips. There is a rapid increase in intensity of soil drifting near the windward edge of a field of highly calcareous heavy clay soil followed by a nearly constant rate of flow along the remaining part of the field, as compared with a relatively uniform rate of increase of erosion across the whole length of the field on loam or clay loam soil (7). Drifting frequently piles the soil in the stubble at the edges of each strip to as great an extent as on the edge of a large field. Stripcropping on this type of soil, therefore, has definite limitations.

Crops on clay soil are usually fair to good, especially if the crop is seeded on well-prepared fallow or on stubble land that has a good reserve of moisture. To prevent soil drifting, every effort must be made to keep this stubble anchored at the surface of the soil (fig. 8).

Although loam soils show a wide variation in their susceptibility to drifting, they are as a class the least susceptible. The actual damage is by far the most serious when wind erosion occurs in these soils, however.

Figure 7.--Sorghum stubble provides effective protection to the soil against wind erosion.

Figure 8.--Stubble-mulch tillage leaves practically all the stubble well anchored on the surface. Wheat is planted through the stubble.

Once drifting starts, there is a gradual separation of the fine soil particles and organic matter from any coarse sandy material, and as drifting continues the soil becomes progressively lighter in texture (fig. 9). The greater the distance the material is moved, the more complete is the separation. It is extremely important, therefore, to check drifting at its source. Drifting usually starts at a few vulnerable spots and spreads over the entire field. For this reason stripcropping has proved to be a valuable aid in controlling soil drift, especially on the loam soils.

Figure 9.--Part of sand-dune area of approximately 175,000 acres in Crane and Ector Counties in Texas. Much of the organic matter, silt, and clay fractions of the original soil have been blown away.

Loam soils have a fairly good moisture-holding capacity and, under normal conditions, the stubble from crops on fallow is enough to form a good trash cover. In addition, these soils tend to retain a cloddy structure which helps to resist wind erosion. Soil drifting on loam soils is relatively easy to control. The damage caused by drifting, however, is so severe that extreme precautions to prevent soil drift are justified.

By maintaining a trash cover or a cloddy condition at the surface, it is possible to control drifting in fields up to 40 rods wide (16). If the stubble is light, however, a sound precaution is to seed a narrow strip of grain about 3 to 4 rods wide down the center of the field before starting to summer fallow. This temporarily reduces the width of the crop strip to 20 rods or less. As conditions improve, these narrow strips can be eliminated.

Since soil drifting on loam soils can be prevented by creating a lumpy surface, by maintaining a trash cover, or by a combination of these measures, a much wider range of cultural practices is possible on such soils than on the light sandy or heavy clay soils.

Wind Erosion Reduces Crop Yields

Topsoil to an average depth of about 9 inches has been removed from certain fields in western Kansas, mainly by wind erosion, during the 19 years the fields have been devoted to the production of wheat (9). The loss included all of the fertile A horizon. This land is now much less productive and contains substantially less organic matter and undecomposed crop residue than when newly broken. Owing to lower amounts of crop residue

this "old" cultivated land is less protected from erosion by wind and water. The soil itself, however, is more resistant to wind erosion now than when it was first brought under cultivation. This is due to the presence at the surface of the finer textured and more highly developed structure of the original B horizon. When the protective influence of crop residues was discounted, the old cultivated land was less than half as erodible as land broken out of virgin sod between 1946 and 1948. With crop failures, such as occur on all types of land in dry years, the recently broken land apparently would be most vulnerable to erosion by wind.

Wind erosion in the Great Plains has reduced the annual potential production capacity of the land 7 bushels of wheat per acre since the land was first put into cultivation more than 30 years ago (14). Four and two-tenths bushels of this 7-bushel loss in yielding capacity are due to removal of fertility by wind erosion. The other 2.8 bushels are due to the removal of fertility by the crops harvested.

Soil fertility was removed much faster by the wind during the first 4 years after active erosion started than during any like period later. The rate of loss for this period was from 4 to 5 times that of later losses. The dust removed by storms during this rapid phase of fertility decline consisted mainly of the rich, black organic matter and the silt and clay of the topsoil. These duststorms are known as "black rollers" (fig. 10). Materials composing the dust are the more fertility-bearing portions of the topsoil. Erosion reduced crop yields more rapidly during this early period of active erosion than later. Fertility elements removed by crops were in direct proportion to crop yields.

Figure 10.--Duststorms during the first few years after virgin land is put into cultivation contain much rich black organic matter, silt, and clay from topsoil and are known as "black rollers."

The effects of lost fertility have been masked or offset by improved crop yields resulting from the use of improved varieties of wheat and by better tillage. It has taken new, higher yielding wheats and better cultural practices to make up for the 7-bushel decline in yield caused by loss in soil fertility.

Cropping Practices and Wind-Erosion Control

The best means of preventing wind erosion on cropland is to keep a vegetal cover on the land continuously. The effectiveness of vegetal cover in preventing wind erosion was

amply demonstrated during a duststorm at Salina and McPherson, Kans., in March 1950 (8). During the storm, wind erosion occurred only on fields which did not have enough vegetal cover. Wherever the crop residue on the surface amounted to a ton or more per acre, little, or no erosion occurred; but where the vegetal cover was not enough, topsoil to an average depth of about 0.85 inch was removed.

The effectiveness of organic residue retained at the surface to prevent wind erosion is due mainly to the reduction in wind velocity, and, to a lesser degree, to the high capacity of the residue to trap the eroding soil.

The amount of wheat stubble or straw required to prevent erosion by wind varies with the relative erosiveness of the soil and the velocity of the wind. The higher the velocity of the wind, the greater is the amount of crop residue required. Studies in Canada have shown that the amount of stubble needed to give equal protection had to be doubled to withstand an increase of 5 miles per hour in wind velocity at the 1-foot height (6). Short stubble provides less protection to the soil than an equal amount of longer stubble.

Stubble provides less ground coverage than an equal weight of straw, but is less subject to removal by high winds. The combination of straw scattered on the ground surface and stubble provides more protection against the wind than equivalent amounts of straw or stubble alone (fig. 11).

Figure 11. --A cover that furnishes a high degree of protection to wheatland against wind erosion is provided by leaving a high stubble and spreading the chaff during combine harvesting.

Cropping systems and cultural operations should be directed toward the maintenance of surface covers of growing crops or undecomposed residues. The condition of the soil surface as to roughness, coarseness, and cover--all of which help the soil to resist blowing--is determined to a large extent by the method of tillage.

Row cropping may place the surface in condition to blow. When such crops as corn and sorghum are harvested, either the stubble should be left about a foot high or higher (fig. 12) or at least 2 rows in 20 should be left standing. If these crops are pastured, the stock should be removed while there are still enough stalks with leaves attached to furnish protection. Stripcropping aids in the control of soil blowing by shortening the distance that loose soil can move. If the strips are laid out on the contour, water also is conserved, which in turn helps prevent blowing.

Figure 12.--Corn and sorghum stubble should be cut at least a foot high for effective wind erosion control.

The soil-blowing hazard on summer-fallowed land may also be reduced by carrying on cultural operations in the manner which results in a minimum of soil disturbance: for example, controlling weed growth with subsurface tillage or by chemicals, cultivating wherever possible only when the ground is moist, and using types of tillage tools that do not pulverize the soil. Cutting corn and sorghum stubble so as to leave a fairly large amount of leaves usually will protect the soil from blowing provided they contain enough foliage (fig. 13). Land left over winter in grain stubble or with a cover of weeds will not blow, and winter wheat with a good fall growth usually protects the soil sufficiently.

Because of climatic conditions the lands of the central Great Plains, if not protected by vegetal cover, are more subject to severe wind erosion than almost any other agricultural area of the world. In this area, both drilled and row crops should be planted in rows running at right angles to the direction of the prevailing winds or on the contour. Land in wheat 2 to 4 inches high lost 2.5 times as much soil by wind erosion when planting was in rows parallel to the direction of the wind as when planting was in rows at right angles to it (25). The additional obstruction presented by the wheat in rows at right angles to the wind direction accounted for a large part of this difference. The safest practice is to return all fields west of the 20-inch rainfall belt in the Great Plains to grass, at least on a rotation basis, for a period of 5 to 7 years. Such a rotation is more likely to maintain the much needed crop stubble and other residues for wind-erosion protection, improve soil structure, and promote other favorable conditions than is the conventional cropping system (19).

The wind-erosion problem is so complex that only by a combination of measures can a successful program of wind-erosion control be provided and maintained and future serious damage prevented. To completely repair erosion damage, even if it were possible, would be costly and uneconomical. In the struggle against wind erosion, preparations 10 to 20 months in advance of probable hazard conditions can be made in connection with productive crop management and will not only protect the capital investment but prevent expensive repair operations later (fig. 14).

Among the crops adapted to southern Great Plains conditions which have erosion-resisting residues are the winter and spring grains--wheat, barley, oats, and rye. Of these, winter wheat is of foremost importance. Grasses grown for seed, hay or pasture,

Figure 13.--The haze in the background is caused by dust from an unprotected wheatfield. The land in the foreground is protected by sorghum stubble and the soil is not blowing.

Figure 14.--Preparations made 10 to 20 months in advance often prevent costly wind-erosion control in the future. On this field milo has been seeded for stubble in which to seed sideoats grama in following spring.

are excellent erosion-control plants. The row crops which leave erosion-resisting residues are all of the sorghum family, among them milo, kaffir, hegari, broomcorn, and sudangrass. The mere growing of any of these crops does not necessarily give erosion protection to the soil in which they are grown. The ideal system of management for wind-erosion control requires that the surface residue be returned. It is best to leave the residue cover on the surface and to plant through the residues for the next crop. The growing crop then perpetuates the ground cover and provides at the close of the season a renewal of the residue supply (fig. 15).

Figure 15.--Ground cover can be perpetuated by seeding new crop through the stubble and other residue of preceding crop.

The practices of burning stubble and overgrazing stalk fields have no place in a wind-erosion control program. Some of the most severe wind erosion in the Panhandle area of the southern Plains is directly attributable to these two destructive practices. Rank wheat stubble has often been burned because of the mechanical difficulty of working it into the soil and because of the temporary fertility depression that often follows when the stubble is retained. These are more than compensated for by the protection provided the soil when the stubble is left unburned and by the ultimate increase in productiveness. Methods have been developed for leaving this straw on the surface of the ground and planting through it. The temporary depression in crop yields can be overcome by proper use of nitrogen. In addition, the use of crop residues on the surface of the ground increases the rate of water absorption and the water-retention capacity of the soil. If a droughty season follows, this advantage more than offsets the fertility depression. The reverse may be true, however, if another favorable season follows, but the odds against two bumper crops in succession are too high to risk exposing the soil to wind erosion by burning the straw. Another practice that has resulted in just as disastrous consequences is that of renting stalk fields to outside herdsmen, who almost invariably leave the cattle in the field until the last scrap of vegetation has been consumed. Moderate stalk-field grazing benefits farm livestock, but the livestock should be removed when the effectiveness of the ground cover is threatened.

Where sorghum crops are cut with a binder for fodder, either a uniform stubble at least 1 foot high should be left, or regular strips 4 to 6 rows wide should be headed and the intervening space of 20 to 30 rows harvested for forage. A good stand of any of the sorghum varieties will protect the soil from the wind if this rule is followed.

Heavy wheat stubble and thick stubbles of close-drilled sorghums left 1 foot high or higher may be worked into the surface soil as soon as convenient. Still better, plantings of the next crop may be made in the standing stubble and surface residues (fig. 16).

Figure 16.--Wheat planted in this stubble was well protected from wind erosion.

When corn and other clean-tilled crops which provide little protection against erosion are grown, stripcropping with sorghum or suitable grass is necessary (fig. 17). On light sandy soil, the rows should run about at right angles to the direction of the prevailing winds. The erosion-resisting strips should be spaced closely enough to protect the non-erosion-resisting crop. The windbreak strips should be not less than 4 rows wide, and may be wider depending on the number of rows listed or cultivated at one time. Under severe blowing conditions, the width of main crop strips generally should not be greater than 20 rows, although the actual width will depend on soil type, direction of rows, and type of crops involved. Under severe erosion conditions, strips as narrow as 5 rows may be practical.

Where both drilled crops and row crops are grown on terraced fields, and it is desired to stripcrop, winter grains and other drilled crops can be planted in the irregular "point-row" areas between strips. This not only makes it possible to lengthen the row-crop strips but improves conditions for crop diversification as an aid in the control of wind erosion.

No rigid system of either continuous culture or rotation has been devised that can equal a flexible cropping plan in economy of production. Such a plan takes into consideration the soil-moisture and fertility conditions of individual fields at each successive planting period of the year. Crops should be selected which will provide the maximum cover under these varying conditions.

The dependability of crop production under the variable system assures a continuity of plant cover. The need for emergency crops depends on the success attained in producing and maintaining the residues.

The normal residues of cultivated crops in the winter wheat areas, if properly managed, should provide ample cover except during periods of prolonged drought. Where no vegetal cover is produced because of crop failure, measures should be taken to make sure that the maximum possible amount of precipitation enters the soil for use by the next crop. Emergency cover crops may be planted when normal moisture-saving practices

Figure 17.--Wind stripping with corn and sorghum for protection of corn from wind erosion.

fail to produce enough crop growth to supply the needed cover. If the summer has been too dry to produce a crop and the surface residue has disappeared and rains occur in late summer, a stooling sorghum such as sudangrass, hegari, or dwarf yellow milo should be planted to renew the ground covering for the winter. When winter wheat fails and the land is still bare as the summer season approaches, a dual-purpose planting of wide-row sorghum for grain is in order as a substitute for summer fallow. Milo or similar crops grown in rows 10 to 15 feet apart provide a desirable partial fallow effect and at the same time give stubble protection against blowing until wheat is again planted the following fall and provides a ground cover.

Beans, cowpeas, and similar crops should be grown in strips between the strips of sorghum, sudangrass, or corn (fig. 18).

Adequate supplies of soil moisture hold the key to the successful maintenance of ample crops and crop-residue cover. Those practices which are most effective in controlling wind erosion are also effective in getting greater amounts of the rainfall into the soil. The use of vegetal cover, contour cultivation, and level closed-end terraces is important in this connection. These practices are effective in reducing runoff even during the hardest rains.

In the spring wheat areas, the practice of fallowing, generally assumed to be essential for the conservation of moisture, provides large areas of bare land. The practice of a plowless fallow to leave all residues on the surface has been assumed to be one of the most effective methods for protection against wind. However, under certain conditions this practice breaks down also. Under this system, 21 months or more must elapse between the harvesting of one crop and the initial growth of the next. Near the end of this period, when protection is most needed, residues may be so decomposed as to be of little value for protection against wind.

In some spring wheat areas, stripcropping with maintenance of as much crop residue as possible has been adopted as a regular practice to reduce the hazards of wind erosion. Cover crops are seeded on fallow usually about August 1 as an additional protection. Experiments have indicated that if the cover crop does not exceed 6 inches in height, little reserve moisture is lost from the fallow. The moisture used up by the cover crop may be regained by additional amounts of snow trapped. Thus, yields on cover-cropped

Figure 18.--Beans, potatoes, cowpeas and similar crops should be grown in strips between strips of sorghum, sudangrass, or corn.

fallow are often about equal to those on bare fallow, although some decreases and some increases in crop yields have been recorded. Pasturing cover crops to the extent of not destroying their protective value is feasible and profitable in some regions.

Considerable acreages of land now in cultivation in the southern Great Plains, especially along the western edge, either are too sandy or have too little rainfall for dependable annual crop production. These lands should be put back to grass. Other parts of the western sandy lands are capable of producing excellent crops, especially sorghums. If they are farmed in large blocks, however, soil drifting may, at critical times, spread quickly from one field to another and involve whole neighborhoods. Farmed fields should be small and guarded by permanent plantings of grass or browse plants. With reasonable sized holdings, there is no reason why soil blowing cannot be controlled, even in years of drought, by the proper management of crop cover and proper methods of cultivation. Regrassing by natural or artificial means on the shallower, more sloping, and sandier portions of the Plains is important.

Legumes and grasses used in a rotation with field crops have been found to be effective in reducing the wind erodibility of irrigated soils. For example, land in potatoes after 40 years of cropping to a 3-year rotation of potatoes, beets, and barley lost 74,000 pounds of soil an acre by wind erosion in the spring of 1951 (26). Where 3 years of alfalfa had been included in the crop rotation, the soil lost from the land in potatoes was only 970 pounds per acre. Land cropped to wheat continuously was 4.4 times as erodible as wheat after second-year sweetclover. The yields were 19 and 45 bushels an acre, respectively.

Terraces Support Cropping in The Wind-Erosion Control Program

Uniform distribution of the moisture supply within a field is essential to the establishment of adequate vegetal cover and a wind-erosion control program. For example, a droughty knoll or slope of only a few acres may start erosion that will spread to or menace well watered parts of the same or adjacent fields.

Thus, level terracing (except on the heavy soils) and contour tillage, which have demonstrated their effectiveness in increasing the average soil-moisture supply by about

25 percent under High Plains conditions, have become a very material support to the vegetative program. This type of soil management results in saving water for productive purposes which is needed to help bridge droughty periods in the maintenance of a vegetal cover for erosion prevention. Level closed-end terraces are of doubtful value on the heavy soils. The infiltration rate of these soils is so low that the water would stand in the fields long enough to damage the crops.

In the area of 20 inches average annual rainfall or less, it was formerly believed that all terraces built on gently rolling and nearly level land should be level with closed ends and high enough to back water to the base of the next terrace above. Recent studies, however, indicate that open-end terraces may be best where stubble-mulch tillage and other conservation practices are used. The most practical terrace interval can be determined by linear spacing of terrace area rather than by vertical spacing. The average distance between terraces on silty clay loam wheatlands in the Plains should be 125 to 150 feet. On typical areas of this kind of soil the vertical interval can range from 0.4 to 1.0 foot, the effective height of the terraces being adjusted accordingly. Where small areas of a field are very uneven, splice terraces should be built if the uneven distance exceeds about 250 feet, and terrace sections should be eliminated where the distance falls below 75 feet. Terraces ending in midfield or abutting the edge of the field should have closed ends.

It sometimes becomes necessary to change the vertical interval within a field. On the High Plains, terraces are designed to retain the water that falls within a given area. Use of a fixed vertical interval on land with slopes that average less than 1 percent, causes extremely wide variations in linear spacing where relatively small variations in slope occur. This fact, together with the importance of getting water to all parts of the field, makes adjustment of vertical interval and terrace height necessary.

The terrace cross section best suited to wheat farming is low and broad. A broad crown facilitates the use of machinery in maintaining the terraces. A properly built wheatland terrace can be cultivated and planted the same as any other part of the field. It can be maintained with one round of a one-way disk plow around the terrace annually.

Loam soils used for diversified farming should be terraced in the manner described for wheatland, except that the distance between the terraces should be 150 to 200 feet: A narrower base may be used, if row-crop production alone is to be practiced on loam soil, but in all cases under semiarid conditions a terrace base of 30 feet or more is desirable.

Windbreaks

Windbreaks can be used to control wind erosion where the rainfall is enough to support trees (fig. 19). The utilization of trees as windbreaks in humid areas where wind erosion constitutes a problem is relatively simple. Since moisture is not a limiting factor, the trees can be planted in accordance with a standard pattern. However, standard patterns are not always feasible in areas of limited rainfall. Occasionally, the pattern of tree planting in such areas must be made to conform to the topography of the land rather than to a standard pattern. By conforming to the topography of the land, better advantage can be taken of the limited amount of water available. This plan provides for planting trees in low places where water tends to accumulate during rains, drainageways and similar places, or where snow accumulates in the winter.

The principal value of trees in wind-erosion control is in the broader protection they give to cultivated fields which may start to blow as a result of exposure to dust swept from bare roadways. Windbreaks scattered over a wide area help to break up the surface wind currents which otherwise would sweep the ground without obstruction.

Along highways where snowfall is heavy, tree windbreaks should be placed on the lee side of the road. Naturally favorable sites exist along level stretches of the roadway where surface waters collect, stand in the ditch, and soak into the soil, thus providing an important additional moisture supply to enable tree maintenance without cultivation or irrigation. Other naturally favorable locations occur along drainageways and small lakes in pasture areas along farm roads. The control of erosion by appropriate vegetation may also help to improve conditions for planting on adjacent areas. Sites of this type should be developed with strict regard to the availability of water from the drainage area. In some areas, it may be possible to obtain water for the trees by means of diversion structures.

Species suitable for windbreak plantings which have proved their hardiness in the Panhandle area include Chinese elm, Russian mulberry, honey locust, Russian olive, green ash, cottonwood, and tamarisk.

Figure 19.--A cottonfield protected by windbreaks. The soil is sandy and the farm divided into fields of 15 to 20 acres each by 3-row windbreaks.

Temporary protection against rabbit injury is necessary for tree stock until the trees are large enough to withstand attacks. A permanent rabbit guard of wire netting is preferable.

The suitability of trees for windbreaks varies with soil type, moisture supply, and other functions. In general, tall-growing trees should stand from 8 to 10 feet apart in the row and should be interplanted with the more shrublike species.

Wind-tunnel studies of the flow pattern of wind over model barriers and windbreaks show that the sharper the barrier the more complete is the protection provided (23). Rounded shapes have a lesser zone of influence than narrow vertical shapes. The porosity of a barrier decreases the degree of protection downwind but at the same time extends its zone of influence.

The prevailing ratio between ground-wind velocity and standard velocity in the open is about 0.74, although this changes somewhat with the velocity and is about 0.01 higher at 20 inches than at 16 inches above the ground surface (1). The ratio between the wind velocity at the surface of evenly mowed grass and standard velocity is about 0.50--a clear indication of the extent to which the frictional drag of even minor vegetation tends to reduce velocities. The ground wind is constantly lagging because of ground friction, but it is ultimately set in motion again by the "pull" of the more rapidly moving currents above it. Since the stilled airmass also has depth, the pull of free-moving currents which have passed the ends of the shelterbelt, and can act on the sides of this mass, also is important. Thus the ground pattern of tangible reductions due to a windbreak is never rectangular, but tends to be narrowed toward its outer limit at the same time that the block of stilled air is being thinned to a wedge by the overhead current.

If the wind is diagonal to the barrier and the breadth as well as distance from the belt is calculated, so as to obtain an area measure expressed in area units of height times length of barriers (HL), the summation of all wind reductions give the "HL units."

On the basis of this approach, a 15-mile-per-hour wind has from 11 to 12 units for a single barrier. Higher wind velocities have more units and lower velocities will have fewer units, but aside from this, an expression results by which we can directly compare in a single term the effectiveness of two barriers differing widely in dimensions, proportions, or composition.

The value of four wind barriers separated respectively by distances of 25, 20, and 30 times their common height is approximately the same as four barriers of equal length and type acting independently (1).

In addition to protecting the soil from erosion, windbreaks planted around farmsteads render another valuable service (fig. 20). By reducing wind velocities in the winter, they reduce the fuel requirements for the farmer and the feed requirements for the livestock (2). They may reduce fuel requirements from 25 to 34 percent, depending on the way the windbreaks are laid out, their height and density. Livestock that have the advantage of protection by windbreaks require less feed and gain weight more rapidly than those not so protected.

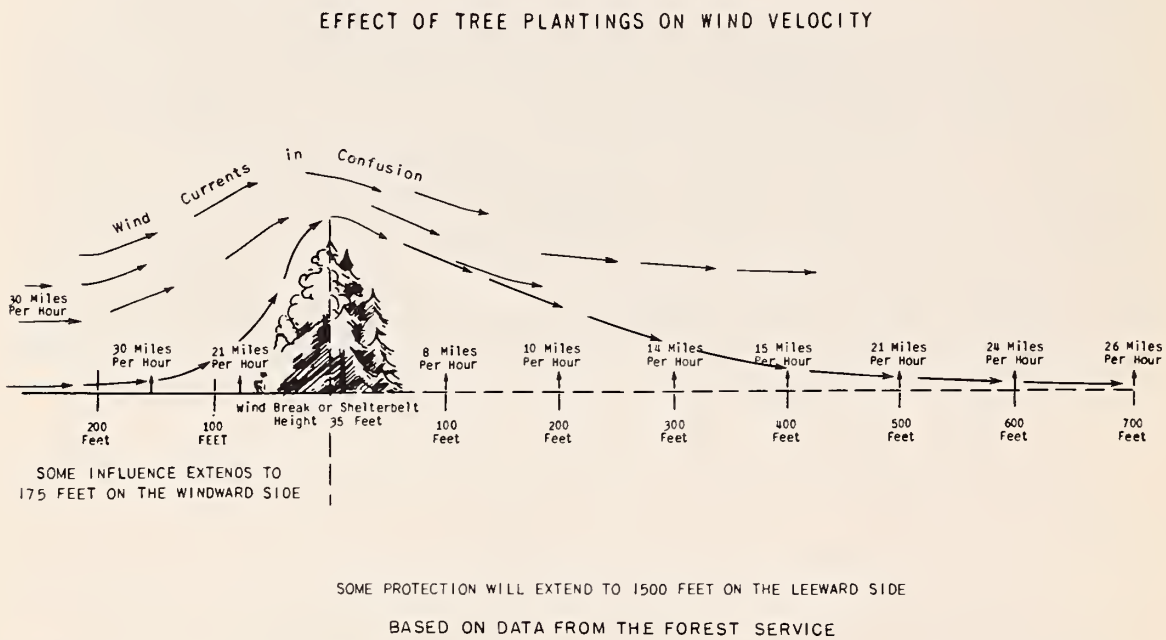

Figure 20.--Windbreaks break up the surface wind currents which otherwise would sweep the ground without obstruction. They provide some protection on the windward side but the greatest protection occurs on the leeward side.

Tillage and Wind-Erosion Control

As previously stated, the best way to prevent wind erosion is to keep the surface of the ground covered with vegetal cover at all times. It follows that the more often a soil is cultivated and the greater the length of time it lies bare and exposed to the action of the elements, the more apt it is to be damaged by wind erosion.

It is equally true that the system of managing land which results in keeping the most residue on the surface will generally be most desirable from the standpoint of erosion control. Stubble-mulch tillage makes it possible to carry heavy residues over into the second year. This is important in years when the crop fails or fails to produce an appreciable amount of protective cover. Tillage operations aimed specifically at erosion control alone should be used only as a last resort.

Delayed stubble-mulch tillage--leaving stubble mulch undisturbed until weed growth is sufficient to require cultivation the following spring--is the most effective method of controlling wind erosion. It is also as satisfactory as other methods of tillage from the standpoint of wheat production. At Amarillo, Tex., for the 9-year period 1943-50, for example, average annual acre yields of wheat were identical for early and delayed fallow. The yield in each case was 20.1 bushels (19). With delayed fallow, all of the crop residues can be left on the surface of the ground for protection during the winter and spring months.

Residues left standing, as with delayed fallow, are more effective than plowed residues for controlling wind erosion during the winter and spring blowing season. This is especially true following years of low crop yields or crop failures, when only small amounts of crop residues are produced. Even with stubble-mulch tillage following harvest, as practiced with early fallow, some of the effectiveness of the stubble for controlling wind erosion is destroyed.

When the soil is bare, any tillage that roughens the surface gives temporary protection from erosion. This can be done by ridging or clodding the surface soil, or by raising subsoil material to the surface.

Among the implements which have been used for ridging and clodding are the lister, shovel or sweep cultivator, deep furrow drill, spring-tooth harrow, plow, and pocket digger. Implements which have been used for bringing subsoil to the surface are the subsoil plow, moldboard plow, lister, disk plow, and grading machine. If considerable crop residue is present, drifting can generally be controlled by subsurface tillage. If crop residue is lacking, however, the land is more likely to drift when subsurface tilled than when it is plowed or listed, because subsurface tillage does not leave a sufficiently cloddy surface.

Shallow tillage when the soil is moist increases clodding of sandy loam soil. The object of raising heavier soil material from the subsoil is to produce a more cloddy structure in the surface soils which have become unstable. Although operations of this character may do permanent good, under certain conditions they are costly and should be considered only as a temporary substitute for measures which provide vegetal cover. The organic matter produced in the surface soil by a vegetal cover serves the same purpose, provides certain other advantages, and the method costs less. Vegetal cover renewed once a year gives more lasting protection than mechanical control measures. It aids in maintaining soil fertility and in keeping the rate of moisture absorption at a high level.

Tillage methods at best offer only temporary relief and, if used, must be repeated at intervals during the season. They are usually uneconomical. In no case should they be substituted for vegetal cover, once conditions become favorable for starting either a regular crop or an emergency cover crop. Tillage practices should be employed to the maximum when all other measures have failed.

Where erosion-prevention tillage can be performed in conjunction with necessary soil preparation or moisture-saving practices, its usefulness is much increased. For maximum moisture conservation, they should be carried out on the contour.

Reconditioning Lands Damaged by Wind Erosion

The most common effect of wind erosion consists of removing the topsoil to plow depth and piling it up in hummocks or drifts (fig. 9). Many hummocked fields are so rough that equipment cannot be driven over them.

The first goal in reconditioning wind-eroded soil is the establishment of vegetal cover over the area affected (fig. 21). This must be preceded, where necessary, by leveling to permit ordinary farming operations and accumulation of sufficient moisture to support the crop to be grown.

The leveling operation may be carried out by the use of wind intensifiers, drag poles, or tractor and road grader (21, 22). Gunny sacks filled with sand and placed at different spacings on the crests of dunes are effective wind intensifiers. After the sandbags are in place, channels about 3 feet wide and 4 feet deep should be dug across the dune and the sand carried out beyond the crest. The sandbags are lowered as the wind removes the sand from around them. Instances have been observed where this method lowered a dune about 2 feet during a single storm, flattening the crest and forming a small dune 6 to 10 feet farther on.

A drag pole, 8 by 8 inches and sufficiently long to extend down the leeward slope of a dune from the crest to the base, may be dragged along the sharp edge at right angles to the crest. A tractor and road grader may be used to level up the field directly or to cut wind channels in the dunes parallel to the direction of the wind. One or more turns over the highest points removes enough soil to give the wind a chance to continue the process. A 20-foot dune, prepared for wind-blast action by this method, was leveled to 5 feet during a 6-month period, putting it in condition for planting. Deep listing may also be beneficial.

Broomcorn and sudangrass are satisfactory plants for use in stabilizing dunes. These plants are more resistant to wind action than a number of other crops grown.

Figure 21.--The soil of this field was stabilized by seeding to sudangrass and sorghum. The area was badly eroded when the planting was made.

Figure 22.--The main defense lines of trees are located at right angles to the direction of the prevailing wind. The secondary defense lines of trees should run at right angles to these at intervals of about 20 to 30 rods.

Hummocks and drifts usually form about weeds and contain a relatively high amount of unrotted organic matter, though much of this may be in a finely pulverized condition. An ample moisture supply is necessary to return areas of this kind to crop use. Until enough moisture is available to start plant growth, further erosion should be prevented by appropriate tillage treatment. This should be supplanted by vegetal-control measures at the first opportunity.

Similar treatment should be given to areas where the topsoil has been removed. The greatest need on such areas, however, is a renewed supply of organic matter, which can only be accumulated from successive crops.

Needed moisture-conservation measures may be combined with reconditioning operations. By increasing the moisture supply and improving the natural moisture distribution, they aid materially in hastening an opportunity for the first crop. Field tests indicate that badly wind-eroded areas may be reclaimed for agricultural use in relatively short periods.

Wind-Erosion Control on Muck Land

Wind, besides causing direct soil loss on muck land, may also cause widespread damage to growing crops. Some of the major damages involved in this type of wind erosion occur in Michigan, New York, and California. In Michigan and New York, the major damage occurs in late spring. During this period, the wind picks up large quantities of finely divided material as well as hard, sharp pieces of muck and wood and hurls them against the tender stems of the young vegetable plants. A few days of active blowing may be enough to effectively cut off the above-ground growth of the young plants.

The critical period in the San Francisco Bay area in California is April, May, and June. Here the major damage is done to lands planted to white asparagus, although the production of any crop which does not provide a vegetal or residue cover during the summer is susceptible to damage.

The use of windbreaks is the most effective means of controlling the velocity of the wind, and hence the damage, from the blowing muck in Michigan and New York. They should be placed in rows at right angles to the direction of the prevailing wind (fig. 22).

Tree planting is relatively inexpensive and easy. Dense masses of trees deflect the wind currents upward and off the surface of the land. For each foot of tree height, $\frac{1}{2}$ to 1 rod of protection on the leeward side is obtained. Three rows of trees with a row of taller-growing species in the center serves to accentuate the upward deflection. Thus, by proper selection of varieties of trees and proper spacing of distances and observation of direction of wind, areas can be made relatively free from wind damage. Decreasing the wind velocity prevents blowing out of the crop and erosion of the soil. Tall-growing trees that are hardy, long lived, and rapid in growth should be selected. Low-growing shrub hedges are not desirable nor effective for such purposes.

After the outside boundaries of the area have been determined, the rows of the tallest varieties are planted. The main defense lines should consist of 3 rows at least 8 feet apart with the trees 6 feet apart in the row. The row spacings should be adjusted to the type of cultivating equipment available on the farm. The tallest-growing variety should be planted in the middle.

The secondary defense lines should cross the fields every 20 to 40 rods at right angles to the primary strips. The rows may be single or double, 6 feet apart with the trees 4 to 5 feet apart in the row.

Trees could be planted beside the roadways if trees are not set closer than 1 rod from the road. They should not be planted where the roots can penetrate tile lines and choke them up. The potential possibilities of muck-land soils cannot be fully realized until sufficiently large plantings of trees are established to break the wind and prevent it from damaging crops and soil.

Rye seeded in the fall may be used as a temporary windbreak under certain conditions. A few drill rows of rye seeded at the usual time and allowed to grow into the following spring ordinarily makes enough growth by late May or early June to provide considerable protection. A few drill rows of rye seeded immediately adjacent to a row of newly started willows make an effective windbreak. The rye should preferably be on the windward side of the permanent windbreak. Oats or barley seeded in the early spring in the manner indicated for rye may be used if rye could not be started the previous fall. These will probably not grow as high as rye but if thickly seeded they may make a denser windbreak at the immediate surface of the muck. The use of these grains, or wheat, greatly improves the effectiveness of recently started windbreaks.

Figure 23.--Dust cloud and funnel formed over asparagus beds on peat soil. The rotating column of air funnels the lighter heated air from near the ground surface to higher elevations.

Oats may be used in single drill rows between rows of onions seeded in the usual manner. The oat rows may be placed from 6 or 7 to 14 onion rows apart.

It is estimated that the windbreak on muck soils protects or checks the velocity of the wind for a distance to the leeward of about 20 times the height of the windbreak.

Cover crops are highly desirable when there is any likelihood of blowing during winter. Under favorable conditions, a cover crop of rye or wheat, planted in pure stand or mixed with oats or barley, covers the soil completely and protects it from the action of the wind.

In addition to providing winter protection, the roots of a cover crop, especially of fall grain, when plowed under for the succeeding crop hold the muck. Moreover, the fresh organic matter provided by the cover-crop materials tends to increase the size of the muck granules. These larger granules are not so easily moved as the smaller ones.

The soils of the Great Plains have been found to be highly erodible by wind when 50 percent of the total material is less than 2 mm. in diameter. By comparison, an average of 74 percent of the peat-soil materials of the San Francisco Bay area is less than this size (24) and, since the specific gravity of the muck material is only about one-third that of sand, these muck soils are extremely susceptible to erosion by wind. It has been estimated that soil loss by wind in this area may be as much as one-fourth to one-half inch per year (20).

In the Delta area of the interior valley of central California, the normal movement of the cool moist winds from the Pacific across the ground surface is upset by the upward movement of heated air rising from the dark ground surface of the muck lands. The result is a turbulent mixing process (24). The extremes of heat exchange are manifested by the formation of rotating columns of airmasses which funnel the lighter heated air from near the ground surface to higher elevations (fig. 23).

It is estimated that approximately 40 percent of the dust movement is due to direct blowing of the wind, 30 percent to dust whirls, and the other 30 percent to factors related to crop culture (23).

Satisfactory methods of wind control have been developed for some of the conditions prevailing in the San Francisco Bay area. They reduce the direct and rotational wind force originating from the bare cultivated ground surface during April-July, the period of

Figure 24.--The first step in stabilizing beach sand is the planting of beachgrass and dune grasses.

highest wind movement. They include the use of protective mulches, residues, stripcropping, or wind barriers in the form of trees, shrubs, or crops. Farmers, however, are reluctant to adopt them as they involve the use of new types of farm machinery with resultant economic difficulties.

Introduction of crop residues as a protective surface cover may require changes in cultivation equipment. A modified system of stripcropping could be carried out in conjunction with the growing of asparagus--the principal crop grown. Such a system should provide either a live or dormant crop growth considerably higher than the crowns of the asparagus ridges during the period April through June.

Coastal-Dune Stabilization

In many coastal areas, the sand washed ashore by wave action is blown inland after drying and is deposited in dunes of various types. Usually the initial product of this process is the formation of a foredune just beyond the high-tide watermark on the shore. As the size of the dune increases, the sand at the crest is blown farther inland where it accumulates and is shaped into another dune. Soon additional dunes are built--one behind the other. Since these dunes are by no means stable, they may level off gradually and supply material for the building of new dunes.

The only permanent solution to this type of problem is the establishment of vegetal cover over the entire surface of the dune. The windward side, being the active part of the dune, should be stabilized first. After this side has been stabilized, the rest of the dune can be brought under control.

Three principal steps are usually required to establish a permanent vegetal cover on coastal dunes. The initial step consists of planting beachgrass and dune grasses to arrest sand movement (fig. 24). Then, intermediate seedings or plantings of leguminous species are necessary as soon as the beachgrass has stilled the moving sand. This step may be combined with the seeding or planting of permanent grasses and legumes or shrubs and trees, if the initial sand-stilling plantings are sufficiently vigorous to have completely stilled the sand.

In establishing initial grass plantings, the order of planting should be from the windward to the leeward side. Plantings should be uniform, without unprotected gaps or strips; otherwise, pockets will be blown out in the dune which may result in the loss of all that has been achieved by previous stabilization activities.

Permanent control of sand dunes can be accomplished only by establishing on them a vegetal cover, either by natural succession or by seeding. Mechanical structures that stop sand movement only temporarily are costly, and, if not properly placed, may cause turbulences that make the dune difficult to stabilize.

Records running back for centuries tell of attempts to hold drifting dunes and prevent the destruction of fertile lands back of them. Before the Christian era, the Pharaohs built great walls along the edges of the plains on either side of the Nile valley to prevent wind-blown sand from covering fertile fields and orchards. For many centuries, the people of Holland have planted and cared for the dunes along their coasts, and have even promoted the formation of dunes to keep back the sea from their homes and fields. The first authentic accounts of successful dune stabilization report the work done by French engineers, who reclaimed the dunes and extensive sand plains along the southwest coast of France. As early as 1778, the French Government sent an engineer, Baron de Villers, to Gascony to study conditions and prepare plans for reclamation. The system proposed by him and later perfected by engineers Chambrelent and Bremontier was the formation of protective dunes on the shore just above high watermark, followed by planting of the dunes with sand-binding grasses and a final planting of maratime and other pines.

The work of planting dunes and sand wastes in this country has been limited. In Massachusetts, from 1826 to 1838, numerous plantings of beachgrass were made on Cape Cod by the Federal Government and by the town of Provincetown. As constant care was not given these plantings, and fishermen and laborers cut the sod and removed the woody growth, the dune lands reverted to their original conditions. Attempts have been made to stabilize dunes along the coasts of Long Island, New Jersey, and the Carolinas. Examples of successful dune control are on the Clatsop Plains at the mouth of the Columbia River in Oregon, in Golden Gate Park in San Francisco, Calif., and along the shore of Lake Michigan in Michigan.

The usual method of starting the grass is to set out plants of beach or marram grass in groups or rows, the spacing depending upon the severity of the wind and on whether the aim is to build up a dune or to still the sand in place. The beachgrass grows vigorously, putting out rootlets at the nodes as these become covered. Care and attention in maintaining sufficient density, and the immediate replacement of plants which have failed, are the chief requisites in the preliminary holding of the dune. After the grass has become well established, seedlings of coniferous trees are planted among the grass. On sand areas leeward of the dunes, the usual method is to cover the surface with brush arranged like shingles on a roof and held down with a shovelful of sand here and there. Seeds of the desired conifers are then sown among the brush.

On active dunes, the planting of grass or other herbaceous plants is necessary for temporarily holding the sand, but forest trees or shrubs must be planted to bring about final stabilization.

Initial sand-stilling plantings of beachgrass were not sufficient to permanently stabilize eroding coastal sand dunes in the Pacific Northwest. Seeding of permanent grasses and legumes was necessary to provide a close permanent vegetal cover over the loose, moving sand (3). Once the dunes became stabilized the beachgrass died.

The dune stabilization work on the Pacific Coast has shown that seeding of grasses and legumes can be made for permanent dune stabilization into 1-year-old plantings of beachgrass if they are vigorous and have stilled the sand. Mixtures of commonly available tame grasses and legumes were better than native grasses and legumes for permanent dune stabilization. The most satisfactory mixture contained hairy vetch, common ryegrass, purple beachpea, Clatsop red fescue, and tall fescue. On rough, undulating dune areas, plantings of pine and Scotch-broom are made instead of these grass-legume seedings, as the herbaceous plants are more difficult to maintain.

On Cape Cod, control measures for small active dunes include the spreading of brush on the windward side of the dune (18). The branches serve as a barrier against the wind and as a trap for catching beachgrass seed. The grass becomes established the following season. Once the grass becomes established well enough to prevent further serious blowing, pine trees are planted. Three to five-year-old pine trees planted in rows about 3 feet apart and with 3-foot spacing in the row are used. The common practice is to plant the trees in early spring, the season when moisture in the sand is most likely to be enough for plant growth requirements.

In stabilizing sand dunes on Cape Henry, it was found necessary to supplement other practices by construction of groins at about 100-yard intervals (15). This structure consisted of a two-strand barbed wire fence and driftwood posts with barberry brush interwoven into the wire. The brush was arranged with the butts placed alternately up and down. The fence, a little over 4 feet in height, extended from the foot of the foredune across the foreshore down to the average high watermark. The seaside end was divided into a short wye, with wings 15 feet long, to protect the end from erosive wave action. A short ell projecting upward at the upper end served to protect the upper end of the structure and prevent scouring of the foredune by oblique winds.

Sandblow areas in Vermont were laid out in alternate 12-and 24-foot strips at right angles to the direction of the prevailing wind. The 12-foot strips were planted to weeping lovegrass and black locust and the 24-foot strips to red pine. The lovegrass seed was broadcast at the rate of 3 pounds per acre and raked in. The black locusts were set at 6-foot intervals in 2 staggered rows in the grass strips. Early the second spring, or during the fall after planting of the lovegrass, red pine was planted in the 24-foot space between the grass-locust strips, using a 6-foot spacing in 4 staggered rows. Ample fertilizer and lime were applied for both grass and trees at the time of planting the grass (17).

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